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## INTRODUCTION

In 1965 the U.S. Geological Survey made an aeromagnetic survey of the Salton Sea area in southern California. The data thus obtained provide information about the subsurface extent of igneous rocks associated with the volcanic domes and geothermal area at the southeast end of the Salton Sea. A ground magnetic survey (Kelley and Soske, 1936) had already indicated a broad magnetic anomaly, several miles in diameter, upon which were superimposed sharp local anomalies associated with the volcanic domes. The new aeromagnetic data indicate that this broad anomaly is actually a protrusion on a northwest-trending magnetic ridge at least 18 miles long. This report discusses the aeromagnetic map and its interpretation, which was aided by measurements of the magnetic properties of rock samples and by data from other reports.

## GEOLOGY

The Salton Sea is in the Imperial-Coachella Valley. The valley occupies an elongate structural trough—the Salton Trough—that extends northwestward from the Gulf of California. Southern branches of the San Andreas fault system, such as the Mission Creek-Banning fault, extend into the trough. The surrounding highlands, and presumably the basement rocks of the trough, are composed of pre-Tertiary igneous and metamorphic rocks (Dibblee, 1954; Kovach and others, 1962). The trough is filled with Tertiary and Quaternary sandstones and shales of deltaic and lacustrine origin, which interfinger laterally with coarser detritus along the margins of the valley. The total thickness of the Tertiary and Quaternary sedimentary rocks in the map area, at the southeast end of the Salton Sea, is not known with certainty, but seismic data obtained by Biehler, Kovach, and Allen (1964, p. 133) indicate that it is between 18,000 and 20,000 feet. These rocks are folded and faulted to a moderate degree, presumably in response to the stresses that produced the structural trough and the San Andreas fault system (Dibblee, 1954; Meidav, 1968).

The Tertiary sedimentary rocks are associated in two nearby areas with rhyolitic lavas (Dibblee, 1954). Miocene(?) rhyolite crops out near Mecca, which is at the north end of the Salton Sea, outside the map area, and Pliocene rhyolite is exposed near Truckhaven, on the west shore of the Salton Sea.

Five small volcanic domes of rhyolite that cut across all but the most recent sediments crop out south of the Salton Sea (Kelley and Soske, 1936). The Salton Sea geothermal area is associated with these domes. Its geology has been described in detail by Helgeson (1968) and by Muffler and White (1969). Thermal springs and mud pots occur in two zones that trend northwest across the area: one passes through the Mullet Island volcanic dome, the other is 2 miles to the northeast (pl. 1). The Imperial carbon dioxide gas field (Rook and Williams, 1942) lies northeast of the Mullet Island, between the two zones of springs. Several wells have been drilled there for $CO_2$ or steam during the past 32 years, and within the past 10 years 10 geothermal wells have been drilled to depths of from 1,695 to 8,100 feet.

Some of the Tertiary and Quaternary sediments and sedimentary rocks in and near the geothermal area have been metamorphosed to greenschist facies mineral assemblages containing chlorite, epidote, and albite (White and others, 1963; Muffler and White, 1969). The metamorphism has reduced the porosity and increased the density of these rocks. The degree of metamorphism increases with depth, primarily because of increasing temperature, which attains 360°C at a depth of 7,100 feet. Sills and dikes of altered intermediate igneous rocks have been intersected at various depths by two of the wells.

## GEOPHYSICAL DATA

The aeromagnetic survey of 1965 was conducted as follows. Total magnetic intensity was measured with a continuously recording ASQ-8 airborne magnetometer. East-west traverse lines were flown at a barometric elevation of 800 feet above sea level, and thus approximately 1,000 feet above the ground in the central portion of the map area. Flight lines were half a mile apart in the vicinity of the volcanic domes, and a mile apart elsewhere. The pilots were guided by topographic maps on a scale of 1:24,000, and the flight path of the plane was recorded by a gyrostabilized 35-mm continuous-strip-film camera. The distance from the aircraft to the ground was measured by a continuously recording radar altimeter. The earth's main field, here having a regional gradient of about 7 gammas per mile toward magnetic north, has not been removed from the aeromagnetic map.

We obtained valuable detailed information from a map (Soske, 1935; Kelley and Soske, 1936) that shows the vertical magnetic intensity at the ground in an area about 8 miles square, centered approximately on the volcanic domes. Profiles transverse to the Salton Trough and the Mission Creek-Banning fault (Soske, 1935) add regional data beyond the limits of the aeromagnetic map and indicate a large northwest-trending magnetic anomaly associated with the volcanic domes. The anomaly probably extends at least 6 miles southeast of Calipatria.

A map of simple Bouguer gravity anomalies in the Salton Trough (Biehler and others, 1964) shows a positive anomaly of at least 20 mgal amplitude associated with the Salton Sea geothermal area; this anomaly reaches its greatest intensity level near well I.I.D. No. 2. The axis of its upper portion (within the -30 mgal contour) strikes northwest from Calipatria to lat 33°20′ N. and corresponds exactly with the northwest-trending magnetic anomaly. Biehler, Kovach, and Allen (1964, p. 138) suggested that this anomaly may be due to an increase in density of the sedimentary rocks, from 0.3 to 0.4 g/cm$^3$, resulting from metamorphism. If the density increase is of this magnitude, a 5,000-6,000-foot thickness of the metamorphosed rock could account for the anomaly.

Seismic refraction data for the Salton Trough region have been published by Kovach, Allen, and Press (1962) and by Biehler, Kovach, and Allen (1964).

To obtain help in interpreting the magnetic data we measured the magnetic properties of several samples of rock from the mapped area (table 1), including unaltered Holocene sediments, an altered dike rock penetrated at moderate depth by a geothermal well, and core samples of sedimentary rocks, metamorphosed to differing degrees, from widely spaced depths in the geothermal wells. We also measured three samples of sedimentary rocks taken from depths of 11,372 to 13,377 feet in Wilson No. 1, an oil-test well 22 miles southeast of the Salton Sea and near the east bank of the Alamo River; these were as little altered as the samples studies by Muffler and White (1969, p. 162) from depths of less than 2,000 feet in the geothermal field.

Both the metamorphosed and unmetamorphosed sedimentary rocks are relatively nonmagnetic and thus cannot cause the aforementioned magnetic anomaly.

TABLE 1.—*Magnetic properties of rocks from the Salton Sea area*
[K, volume magnetic susceptibility; J, remanent magnetization]

| Rock | Well | Depth (feet) | K (emu/cm³) | J (emu/cm³) |
|---|---|---|---|---|
| Siltstone | River Ranch No. 1 | 2,434 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 4,481 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Metasiltstone | Do. | 5,632 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 5,637 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 5,641 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 6,605 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 6,612 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 6,623 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 7,422 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Siltstone | Wilson No. 1 | 11,372 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 12,910 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Do. | Do. | 13,377 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Metasiltstone (most altered) | I.I.D. No. 1 | 4,480 | $4 \times 10^{-5}$ | $<1.7 \times 10^{-6}$ |
| Holocene lacustrine clay | Surface | - | $2.6 \times 10^{-5}$ | $3.5 \times 10^{-5}$ |
| Do. | Do. | - | $4 \times 10^{-5}$ | $4.6 \times 10^{-5}$ |
| Altered porphyritic andesite or basalt (dike) | I.I.D. No. 2 | 3,653 | $350 \times 10^{-5}$ | $3.44 \times 10^{-2}$ |
| Obsidian from Red Island[1] | Surface | - | $29 \times 10^{-5}$ | $1.55 \times 10^{-3}$ |

[1]The Curie temp. of titaniferous magnetite in a bulk sample of this rock is 520°C.

## GEOPHYSICAL INTERPRETATION

The aeromagnetic map shows three major areas of differing magnetic pattern: (1) the magnetic high extending approximately 18 miles northwest from Calipatria to the middle of the Salton Sea and associated with the volcanic domes and the geothermal area; (2) an area of relatively smooth magnetic pattern associated with the Salton Trough and extending outward on both sides of the magnetic high; (3) an area of irregular magnetic field which is on the east and northeast border of the mapped area and which is underlain at relatively shallow depths by pre-Tertiary crystalline rocks. The magnetic anomalies represent variations in the amount and susceptibility of magnetic minerals (chiefly magnetite) and in the intensity of their remanent magnetization.

*Magnetic high.*—The magnetic high of area 1 consists of three superposed sets of magnetic anomalies that differ in order of magnitude. Its dominant feature is the magnetic ridge extending northwestward from Calipatria. Superimposed upon this ridge are two elliptical magnetic anomalies which trend northeast and are approximately 3 and 5 miles long. The longer one is clearly associated with the northeast-trending row of volcanic domes.

Superimposed, in turn, upon the elliptical anomalies are small but locally intense anomalies as much as 90 gammas in amplitude but no more than half a mile wide. Small anomalies of this sort are associated with all five of the volcanic domes, but because of the contour interval of the aeromagnetic map they are more easily seen on the magnetic profiles from which the map was constructed. Flight line 14 crosses over Obsidian Butte and shows a 90-gamma local anomaly (A, map and profile). The north-south tie line records a two-humped 20-gamma anomaly over the two domes of Red Island (anomalies B and C, map and profile), and a 5-gamma anomaly over Mullet Island (anomaly D). There is, in addition, a magnetic feature (anomaly E) with no recognized surface expression. This anomaly presumably represents a concealed volcanic dome or intrusion that, judging by the magnetic gradients, is less than 1,000 feet below ground surface. Anomaly F, a similar feature, is about 1 mile west of anomaly E on flight line 19.

The northwesternmost of the two large elliptical anomalies is not known to be associated with any volcanic domes, but the aeromagnetic data indicate at least two small magnetic features that resemble those described above associated with the domes of the other elliptical anomaly. One of these features (anomaly G) is on flight line 25, and the other (anomaly H) on flight line 19. Anomaly H is especially pronounced and evident on flight line 20 as well as 19. Both anomalies are presumably caused by concealed volcanic domes or intrusive masses that extend to within less than 1,000 feet below the ground surface, and are on a northeast-trending line approximately parallel to the line of volcanic domes associated with the larger elliptical anomaly.

The order of magnitude of the magnetic anomalies associated with these volcanic domes was tested with a computer program written by R. F. McMahon and R. E. McIntire, which produces a total-intensity magnetic contour map from a set of arbitrary parallelopipeds. On the basis of (1) the scanty data on magnetic properties of obsidian at Red Island (table 1), and (2) the assumption that the remanent magnetization is parallel to the earth's field, a horizontal slab of the obsidian 100 feet thick and 1,300 feet square (the approximate dimensions of the south dome on Red Island) would generate an anomaly of about 15 gammas, as measured 1,000 feet above the slab. The anomaly actually observed over Red Island is 20 gammas. A similar calculation was made for the dome on Mullet Island; the rock in this one was assumed to be equivalent to a horizontal slab 100 feet thick and 600 feet square, which yields a calculated anomaly of 5 gammas, whereas the observed anomaly is about the same. The observed results thus agree fairly well with theory for these two islands. The observed anomaly for Obsidian Butte is 90 gammas, and its estimated shape approximately the same as that of a rectangle 2,400 feet long by 1,800 feet wide. A horizontal slab of obsidian that had this shape and yielded this anomaly would, according to our calculations, be 500 feet thick. We are unable to make an independent estimate of the actual thickness of the rock in Obsidian Butte, but a cross-section by Kelley and Soske (1936, fig. 4) indicates that a thickness of 500 feet is not unreasonable. The above results, together with the comparatively small lateral extent of the volcanic-dome anomalies, suggest that the conduits through which the domes were fed are much narrower than the bases of the domes.

A map of the volcanic-dome area showing the vertical intensity of the earth's magnetic field at ground level (Soske, 1935; Kelley and Soske, 1936) indicates that many masses of igneous rock may be concealed at shallow depths beneath the surface. Within the area enclosed by the 1,800-gamma contour on the aeromagnetic map, the ground-magnetic map shows (in addition to the large anomalies associated with the volcanic domes) four subcircular magnetic highs, which may be caused by buried masses of igneous rock, either intrusive or extrusive. The vertical-intensity map also shows several narrow linear magnetic ridges, 0.5 to 1.5 miles long, radiating from these magnetic highs. These ridges have irregular trends ranging between north and northeast; they may represent dikes at relatively shallow depths (less than 1,000 feet below the surface). However, well I.I.D. No. 1, 5,232 feet deep and about 1,100 feet south of the center of one subcircular magnetic high but rather close to its edge, did not penetrate any igneous rock.

It is more difficult to interpret the two large elliptical magnetic anomalies, and although the largest is clearly associated with the row of volcanic domes, it is clearly not directly caused by them.

Kelley and Soske (1936) believed that the whole area is underlain by a large mass of igneous rock. We have arrived at a somewhat different explanation, discussed below.

A series of magnetic-model calculations were made in an effort to simulate the larger of the two elliptical magnetic anomalies. This was isolated from the large linear magnetic anomaly by means of a northwest-trending magnetic profile along its crest. The results yield information about the shape of the causative magnetic mass, on the assumption that it is uniformly magnetized. Its highest part is near the center of the anomaly, and the outward dip of its upper contacts may explain the absence of a local magnetic minimum on its north side. As a limiting case, it was assumed that the top of the mass was at the surface, and the bottom 10,000 feet below the surface. The calculated magnetization for this case is $30\times10^{-5}$ emu/cm$^3$, which corresponds, if we assume a local field intensity of 0.5 oersted, to a magnetic susceptibility of $60\times10^{-5}$ emu/cm$^3$. The calculated magnetization would be only about 5 percent larger if the top of the magnetic mass were 2,000 feet and the bottom again 10,000 feet below the surface. The former calculation sets a lower limit for the average magnetization of the anomaly-producing mass.

Calculations using the horizontal extent of the steepest gradients (Vacquier and others, 1951), on both Soske's magnetic map and the aeromagnetic map, indicate that for both of the elliptical anomalies the depths to magnetic material range from 1,000 to 3,000 feet. Metamorphic rocks were reached by the 10 geothermal wells on the southeast flank of the larger elliptical anomaly, and the magnetization of those rocks is lower, by an order of magnitude, than the lower limit found by the calculation presented above. There is little reason to suppose that the magnetization is appreciably different in the metamorphic rocks near the crest of the anomaly, although the existence of metamorphic magnetite is a thermodynamic possibility in the Salton Sea geothermal system (Muffler and White, 1969, p. 179).

Magnetic igneous rock was identified in two of the geothermal wells. Dike rock at a depth of 3,653 feet in I.I.D. No. 2 contains magnetite and has a relatively high susceptibility and remanent magnetization (table 1). In cuttings from Elmore No. 1, magnetite-bearing igneous rock occurred sporadically at depths of 5,400 to 6,980 feet, and was the dominant constituent between 6,980 and 7,717 feet (the bottom of the hole). As these two wells are near the crest of the southeasterly elliptical anomaly, dike rocks probably extend to within 1,000 to 3,000 feet of the surface along the axis of the anomaly. The airborne and ground magnetic data already discussed indicate, moreover, that other small bodies of magnetic rock lie concealed at shallow depths. Judging from Soske's magnetic map, these might underlie approximately 10 to 20 percent of the area within the 1,800-gamma contour of the larger elliptical anomaly on the aeromagnetic map. Therefore, if the magnetization of these shallow sources is 5 to 10 times as large as the previously calculated minimum average magnetization of $3\times10^{-4}$ emu/cm$^3$, or 1.5 to $3\times10^{-3}$ emu/cm$^3$, the limiting parameters of the calculation will be met. This result is not inconsistent with the data for igneous rocks in table 1. If many of the magnetic masses are vertical tabular bodies, the relatively few wells could easily miss magnetic material. However, most of the wells in the geothermal area are on the southeast flank of the elliptical anomaly and not on its crest, where dike rocks might be most abundant.

The long magnetic ridge extending approximately 18 miles northwest from Calipatria is probably caused by a large igneous mass, about 18 miles long and 3-5 miles wide (roughly outlined on the map). The mass probably fed the smaller intrusions associated with the elliptical magnetic anomalies. It might be a large pluton, a dike swarm, or a combination of both. Independent evidence for its existence is afforded by the large amount of heat evolved in the geothermal area and, more especially, by the huge volume of metamorphosed Cenozoic rocks indicated by the drill hole and gravity data. This evolution of heat also suggests that the mass has been cooling for a long time.

The depth to the top of the mass was calculated using the method described by Vacquier (and others, 1951). Six figures were obtained, ranging from 6,500 to 7,500 feet. Errors may result because the deeper anomaly cannot be distinguished, with certainty, from the shallower ones. Thus, the results may be as much as 1,000 feet too low. The shape of the magnetic mass along profile A-A′ was calculated by testing various configurations with a computer program that calculates magnetic profiles across two-dimensional bodies. It was assumed that the magnetization is uniform and that remanent magnetization is parallel to the earth's main field. The first assumption is, indeed, somewhat inaccurate, but the second is probably correct because of the young age of the intrusive activity. The calculated result therefore cannot be regarded as quantitative in detail, but it should indicate, at least roughly, the shape of the mass and its magnetization. Somewhat more complex shapes were calculated that matched the observed curve more precisely, but these do not differ significantly from the simple shape in profile A-A′ and are not regarded as more realistic. Given the general shape of the mass, one can vary somewhat the depth to the top, the thickness, or the magnetization in order to match the anomaly. These variables are not entirely independent of each other, considering the precision of the data. The bottom of the magnetic mass was assumed to be approximately on the basement surface, 20,000 feet below the aircraft, but the calculation is not very sensitive to the depth of the bottom.

Magnetic igneous rocks that could be parts of this long magnetic mass were penetrated in only one geothermal well. Cuttings from Elmore No. 1 at depths of 6,980 to 7,117 feet (bottom of the hole) consist of 50 to 100 percent gray fine-grained altered igneous rock that is of intermediate composition and contains abundant magnetite. In River Ranch No. 1, the deepest well in the geothermal field (8,100 feet), no igneous rocks were detected, but this well is almost half a mile farther than Elmore No. 1 from the crest of the northeast-trending elliptical magnetic high.

The northeast edge of the large magnetic mass is about half a mile southwest of the magnetic minimum, and approximately in line with the Mission Creek-Banning fault; thus, the fault and the intrusion may be related.

*Area of smooth magnetic field.*—In the area of relatively smooth magnetic pattern extending on both sides of the magnetic high, the magnetic rocks are so far below the surface and the aircraft that local magnetic anomalies are greatly attenuated and smoothed out; the basement here, as previously noted, may be 18,000 to 20,000 feet below sea level. Magnetic profile A-A′ shows that the magnetic low on the northeast side of the elongate magnetic high is caused by the same magnetic body that causes the high.

*Area of irregular magnetic field.*—The magnetic field in the northeastern part of the map is irregular because magnetic basement rocks lie only 500-3,000 feet below aircraft level. As the basement is here covered by a relatively thin sheet of sedimentary rocks, no detailed explanation of individual anomalies is attempted, but the elongate magnetic features here parallel the regional northwest trend of the basement metamorphic rocks in the Imperial Valley region.

On the southwest border of this area the depth to the basement increases greatly and the magnetic field becomes smooth. The boundary here is of much structural and geothermal interest, in that it may be a major branch of the San Andreas fault and may provide channels for recharge of meteoric water to the geothermal system. Gravity and seismic data collected across this boundary 11 miles southeast of Amos, in the southeast corner of the map area, have been interpreted as indicating that it is a fault boundary (Kovach and others, 1962, p. 2869), but the gravity anomaly is rather small (about 10 mgal), and interpretations are rendered difficult by uncertainty regarding the densities of the basement rocks and the sedimentary rocks. A basement configuration was calculated for magnetic profile B-B′, which crosses both the linear magnetic high and the boundary between the areas of smooth and irregular magnetic field. The calculated configuration and magnetic susceptibility of the magnetic mass causing the linear magnetic high are similar to those of profile A-A′. The calculated configuration of the boundary of the magnetic basement rocks northeast of the high is that of a smooth surface dipping about 30° SW. The aeromagnetic data on this map thus fail to support the view that this boundary is a major fault; they indicate, rather, that it was due to downwarping along the northeastern margin of the Imperial-Coachella Valley. It is nevertheless possible, however, that the boundary surface is displaced by a series of minor step faults. The calculated average magnetic susceptibility of the basement rocks is $2.5\times10^{-4}$ emu/cm$^3$, which is a reasonable value. The upper edge of the slope is estimated to be at a depth of 2,000 feet, and the corresponding depth at the Ajax Oil Co. Phyllis well, 5 miles southeast of Amos, is 2,804 feet (Kovach and others, 1964, p. 2868).

This magnetic boundary does not have this wide, sloping magnetic gradient at the north end of the north-south tie line near the north edge of the aeromagnetic map. At that place there appears to be a relatively steep and narrow magnetic gradient on the southwest side of the 1,850-gamma anomaly, which suggests that these two areas of differing magnetic field pattern may have a steeply dipping northwest-trending fault at their mutual contact.

## CONCLUSIONS

The linear magnetic high extending northwest from Calipatria into the Salton Sea is caused by a magnetic mass, probably consisting of intrusive rocks, that is about 18 miles long and buried at least 7,000 feet below the surface. The mass may be about 12,000 feet thick and from 15,000 to 26,000 feet wide, and its apparent magnetic susceptibility is about $6\times10^{-4}$ emu/cm$^3$. The two elliptical magnetic anomalies superimposed on the linear high are caused by magnetic masses that extend upward to within less than 1,000 feet of the surface and whose average apparent magnetic susceptibility is about $6\times10^{-4}$ emu/cm$^3$. The elliptical anomalies are probably due to clusters of small igneous intrusions associated with dikes that extend into the overlying sedimentary rocks. The elliptical anomaly to the northwest may indicate a possible source of geothermal energy, and so may the small, circular, magnetic highs at shallow depth shown on Soske's map. The large volume of metamorphosed sedimentary rock associated with the magnetic anomalies and with the geothermal area shows that large amounts of heat have been generated in this area, doubtless by cooling igneous rocks far below the surface. The presence of the magnetic anomaly indicates that the temperatures of the large volumes of igneous rocks above the basement in the Salton Trough probably do not exceed 580°C, the Curie temperature of magnetite, so that the igneous rocks must for the most part have cooled to a temperature well below their liquidus. The Mission Creek-Banning fault, a strand of the San Andreas fault system, probably extends along the northeast side of the large magnetic mass. Aeromagnetic data suggest that most of the eastern margin of the Salton Trough in this area is underlain by an erosion surface, cut on basement rocks, that dips 30° SW.

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